
The Computation of Flow Past an Oblique Wing Using the Thin-Layer Navier-Stokes Equations

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THE COMPUTATION OF FLOW PAST AN OBLIQUE WING USING THE THIN-LAYER NAVIER-STOKES EQUATIONS*

SUMMARY

Essential aspects are presented for computing flow past an oblique wing with the thin-layer Navier-Stokes equations. A new method is developed for generating a grid system around a realistic wing. This method utilizes a series of conformal transformations. The thin-shear-layer approximation and an algebraic eddy-viscosity turbulence model are used to simplify the Reynolds-averaged Navier-Stokes equations. An implicit, factored numerical scheme and the concept of pencil data structure are utilized. For the first time, some flow fields caused by the oblique wing in a supersonic free stream are computed. These flow fields are discussed, emphasizing the separated vortex flows associated with such a wing.

INTRODUCTION

One of the most innovative concepts for improving the efficiency and performance of aircraft, for commercial transport applications and military missions, is the oblique-wing concept (ref. 1). The attractive properties of this concept were first pointed out by Robert T. Jones in a series of papers (ref. 2). This concept is implemented by mounting a straight wing on a conventional subsonic aircraft such that it can be set at different oblique or sweep angles to the direction of flight. The variable-sweep feature of the oblique wing provides optimum sweep throughout the speed range, from subsonic to low supersonic speeds. As a first step, a computation of the flow phenomena associated with an oblique wing is accomplished by solving the thin-layer Navier-Stokes equations. This paper discusses the computational aspects of determining the flow past the oblique wing. Further, it presents sample computations highlighting the phenomena associated with such a wing.

* This paper was withdrawn from the Tenth International Conference on Numerical Methods in Fluid Mechanics, Beijing, China, June 23-27, 1986, because of the sensitive nature of the subject matter.

COMPUTATIONAL GRID SYSTEM

For a fixed number of node points, the O-O grid topology resolves the flow field better than any other (H-H, C-H, C-O, or O-H) grid topology. The O-O grid topology offers the maximum resolution of the flow field in the neighborhood of the wing, particularly near the leading and trailing edges and near the wingtips. Further, it possesses only regular singularities.

When a boundary of a flow field can be mapped with an analytical function, when the resulting distribution of boundary points is nearly satisfactory, and when the interior grid distribution is less of a concern, conformal transformations provide better flow-field resolutions. They give rise to simple geometrical mapping quantities, and it is easier and more computationally efficient to assemble a grid system with them than by using a differential method.

An algebraic generation method is developed here to generate the O-O grid topology for the study of an aircraft wing. The region exterior to the wing is mapped inside a unit sphere with a series of conformal transformations. This mapping is achieved in three steps. First, the line joining the mid-chord locations of the unswept wing at different spanwise locations is sheared so that it aligns with the Cartesian coordinate in the same general direction. The airfoil sections are sheared in the same manner. Second, the region exterior to each spanwise station is mapped into a near circle using the Kármán-Trefftz transformation. These near circles are transformed into exact circles following a procedure given by Ives (ref. 3). As a result of these steps, the wing is mapped into an axisymmetric body. Third, the region exterior to the two-dimensional body formed in a spanwise plane of symmetry is transformed into the interior region of a unit circle. These three steps map the wing into a unit sphere with a spherical (r, θ, ϕ) grid topology. Figure 1 shows the computational grid system around an oblique wing in the physical domain.

THIN-LAYER NAVIER-STOKES EQUATIONS AND TURBULENCE MODEL

Limited computer resources motivate the thin-shear-layer approximation and a simple turbulence model for the present investigation. This approximation and the turbulence model are described below.

A set of equations that falls between the boundary-layer equations and the full Navier-Stokes equations is used to represent the flow past the oblique wing. This intermediate set of equations is obtained by neglecting all streamwise and spanwise derivatives of the viscous and turbulence stress, conductive heat-flux terms, and any term involving mixed derivatives. These equations are generally referred to in the literature as the thin-layer Navier-Stokes (TLNS) equations. Advantages and limitations of using these equations are discussed by Mehta and Lomax (ref. 4), and Blottner (ref. 5).

A zero-equation turbulence model patterned after that of Baldwin and Lomax (ref. 6) is used. The Baldwin-Lomax model does not require the location of the outer edge of a thin-shear layer. It uses the distribution of vorticity to determine the length scale in the outer region of the shear layer. Consequently, it also uses vorticity in the inner region. The Baldwin-Lomax model is extended for present three-dimensional application. However, this model does not simulate the

transition process, and it gives erroneously zero eddy viscosity in the wake region of a body when the wake is symmetric (ref. 7).

COMPUTATIONAL PROCEDURE

An implicit, approximate factorization method is used to solve the Reynolds-averaged TLNS equations in the spherical coordinate system. The numerical method is formulated in Δ -form (ref. 8); and some parts of it are the same as those given in reference (ref. 9). Because of limited computer resources only steady-state computations are attempted using the diagonalization procedure for the implicit operators (ref. 10) and space-varying time increments.

A useful three-dimensional computation of the the flow past the oblique wing requires a large number of node points that create huge data sets for a solution of the Navier-Stokes equations. These data sets cannot be stored in the main memory of the Cray X-MP/12 class of computers. Therefore, external storage devices and an efficient data-management procedure are required for an efficient computation.

There are two aspects of efficient data management. First, the computer programming language should be such that programming logic is relatively simple. This is achieved by coding the computer program in VECTORAL, a computer language developed at Ames Research Center. This language simplifies the data management between the computer and the external storage device. Second, the organization of the data structure should be relatively simple to use. This is achieved by using the pencil data structure concept (ref. 11), which enables the code to run a huge number of node points with a relatively small computer (main) memory. Data sets are divided into cubes of node points. A stack of cubes, which are of same size, extends from one computation boundary to the other boundary, parallel to a coordinate direction. This stack is referred to as a pencil. Only one pencil of data on which computations are performed, resides in the computer memory at any time and results are stored back on the external storage device. There may be different number of pencils in each coordinate directions. Further details are given by Pan and Pulliam (ref. 12).

DISCUSSION OF RESULTS

Some representative solutions are determined for the following conditions. The free-stream Reynolds number, Mach number, and the angle of wing-sweep are $4.0 \times 10^6/ft$, 1.4, and 65° , respectively. The wing has a $250 - ft^2$ plan area. It has a 14% thick airfoil section at the midspan (wing root) and a 12% thick airfoil section at the tips. The wing is not symmetric about the midspan. The airfoil sections along the leading part of this wing are highly cambered compared to those along the trailing part of the wing.

Calculations are made on a relative coarse grid system (fig. 1) with 42, 85, and 41 node points, respectively, in the r -, θ -, and ϕ -directions. Note that the ϕ -coordinate identifies the different spanwise locations. The mesh efficiency factor (ref. 13), the ratio of surface node points,

and the total number of node points raised to the two-thirds power is 1.25 for the present O-O grid topology, whereas this factor is 0.71 for the H-H grid topology with a zonal approach (ref. 14). For the above grid system, the computation time required per time step is 11 sec on the Cray X-MP/12 computer.

Although the computed results are of a qualitative nature owing to the limited computer resources, they are very useful in understanding the flow phenomena generated by the oblique wing in a supersonic flow. When the angle of sweep is large, there is a significant difference between the upper-surface flow fields at low angles of attack and those at high angles of attack. On the upper surface of the wing, flow is primarily along the free-stream and spanwise direction, respectively, at small and large angles of attack. Further, most of the lift force is generally produced on the trailing part of the wing at low angles of attack, and on the leading part of the wing at high angles of attack.

When the free stream is supersonic, the flow is supersonic almost everywhere around the wing. At high angles of attack, there are distinct pockets of high-speed supersonic flow away from the surface of the wing (fig. 2). These appear to be associated with spanwise vortex patterns. At low angles of attack, a vortex pattern along the wingspan is not observed, but there is spanwise flow next to the surface, near the trailing edge of the wing. Simulated oil-flow patterns generated by particle paths initiated next to the surface, and restricted to remain next to the surface, show regions of flow separation and reattachment (fig. 3). Insight into the nature and formation of spanwise vortex patterns and tip vortices is provided by particle paths initiated away from the surface within the boundary layer and free to move with local velocity. Computationally observed vortex patterns are similar to those visualized in water-tunnel experiments with a wing mounted on the body of an aircraft (fig. 4). Water-tunnel experiments, therefore, are useful to study vortex patterns caused by an oblique wing at moderate and large angles of attack.

CONCLUDING REMARKS

Previous viscous computations of flow past a realistic wing using the Navier-Stokes equations have been done for wings with only one tip (refs. 14-16), whereas the present computations are for a wing with two tips. Essential aspects are presented for computing flow past an oblique wing. Some flow fields caused by the oblique wing in a supersonic free stream are computed. These flow fields are discussed, emphasizing the separated vortex flows associated with such a wing.

The present computation procedure is easy to modify to compute unsteady flows, such as those caused by a two-bladed rotor of a rotorcraft in hover or in a forward flight and that caused by a two-bladed propeller. The method developed in this study for generating a grid system around a realistic wing can be used for constructing a grid system around the rotor or the propeller.

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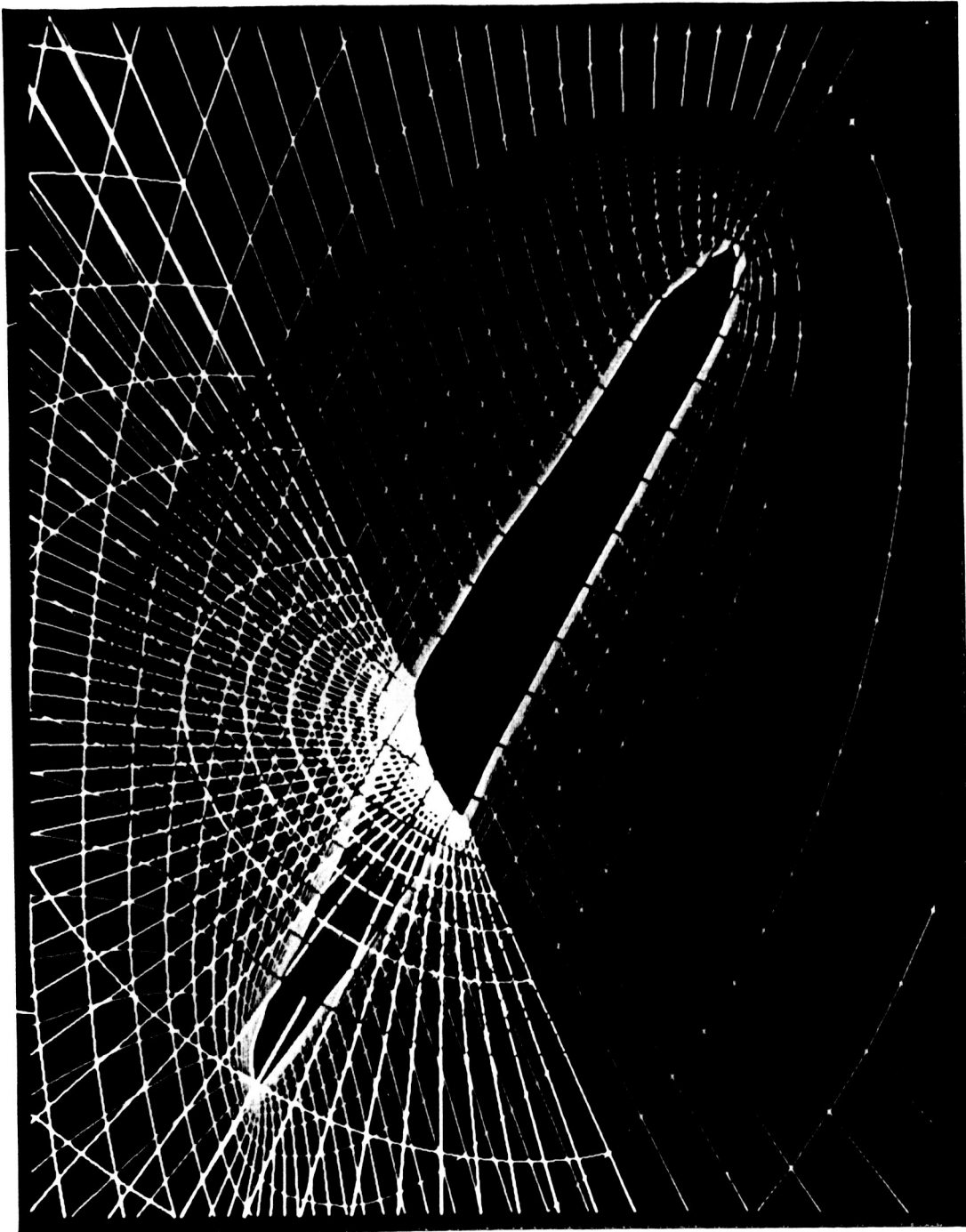


Figure. 1. Computational grid system around an oblique wing.

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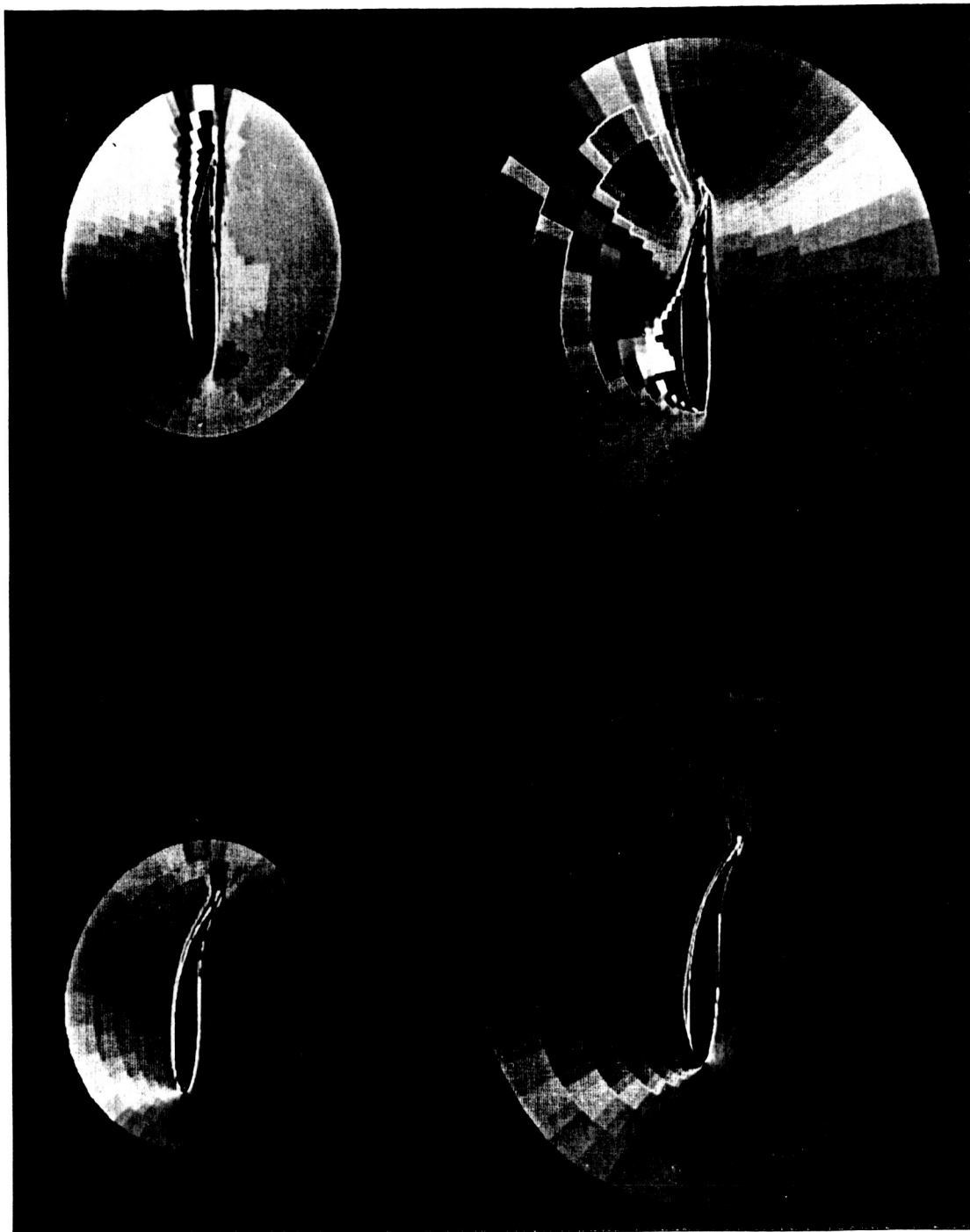


Figure 2. Mach number distributions for $\alpha = 2^\circ$ (top) and 10° (bottom) are shown by the color sequence white, cyan, yellow, red, and magenta, including blends of neighboring colors correspond to Mach number variation from 1.0 to 2.0 with an increment of 0.05. Pictures on left and right correspond to the spanwise location shown near the leading and trailing tip, respectively.

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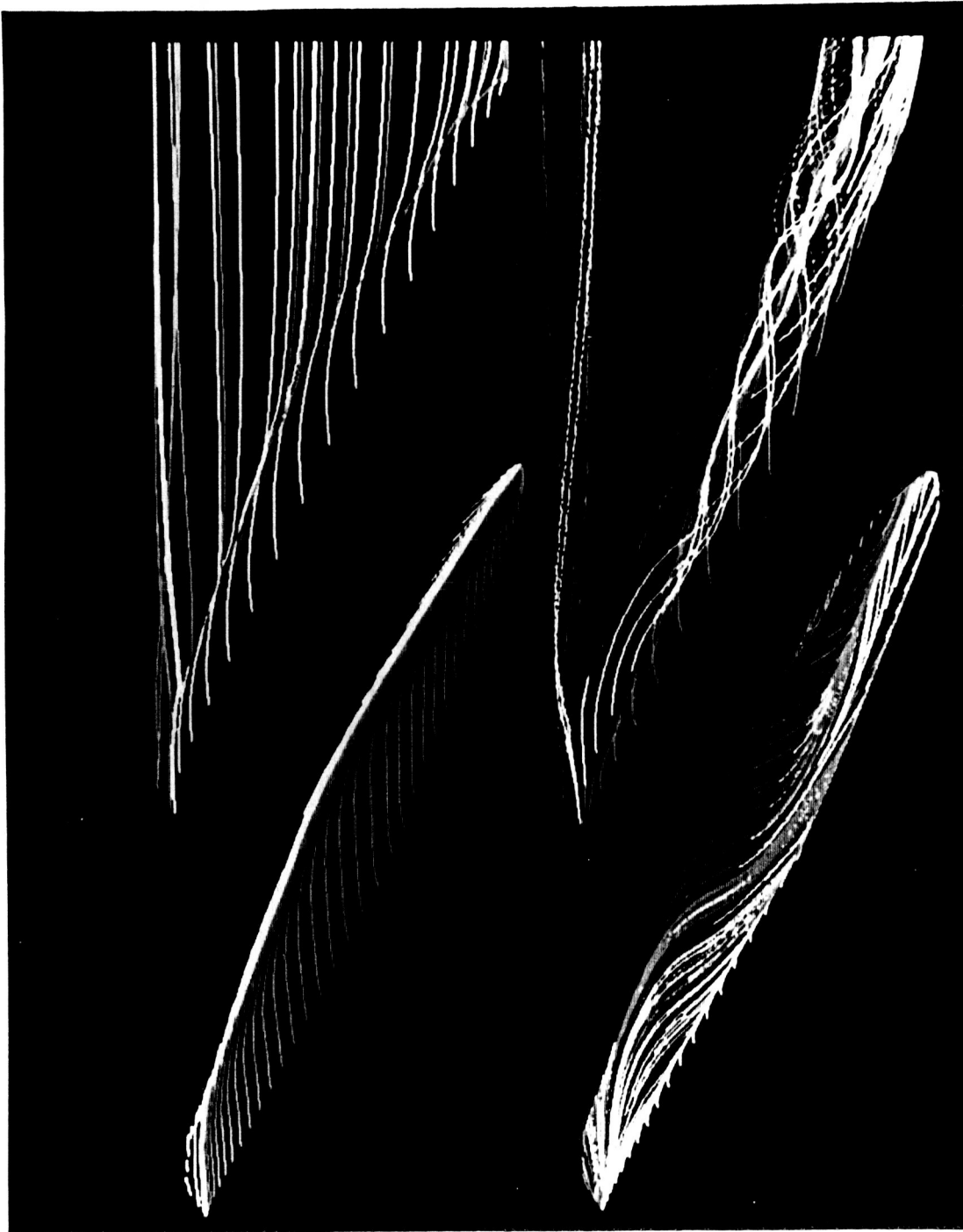


Figure. 3. Simulated oil-flow patterns (left) and particle traces (right)
on the upper surface for $\alpha = 2^\circ$ (top) and 10° (bottom).

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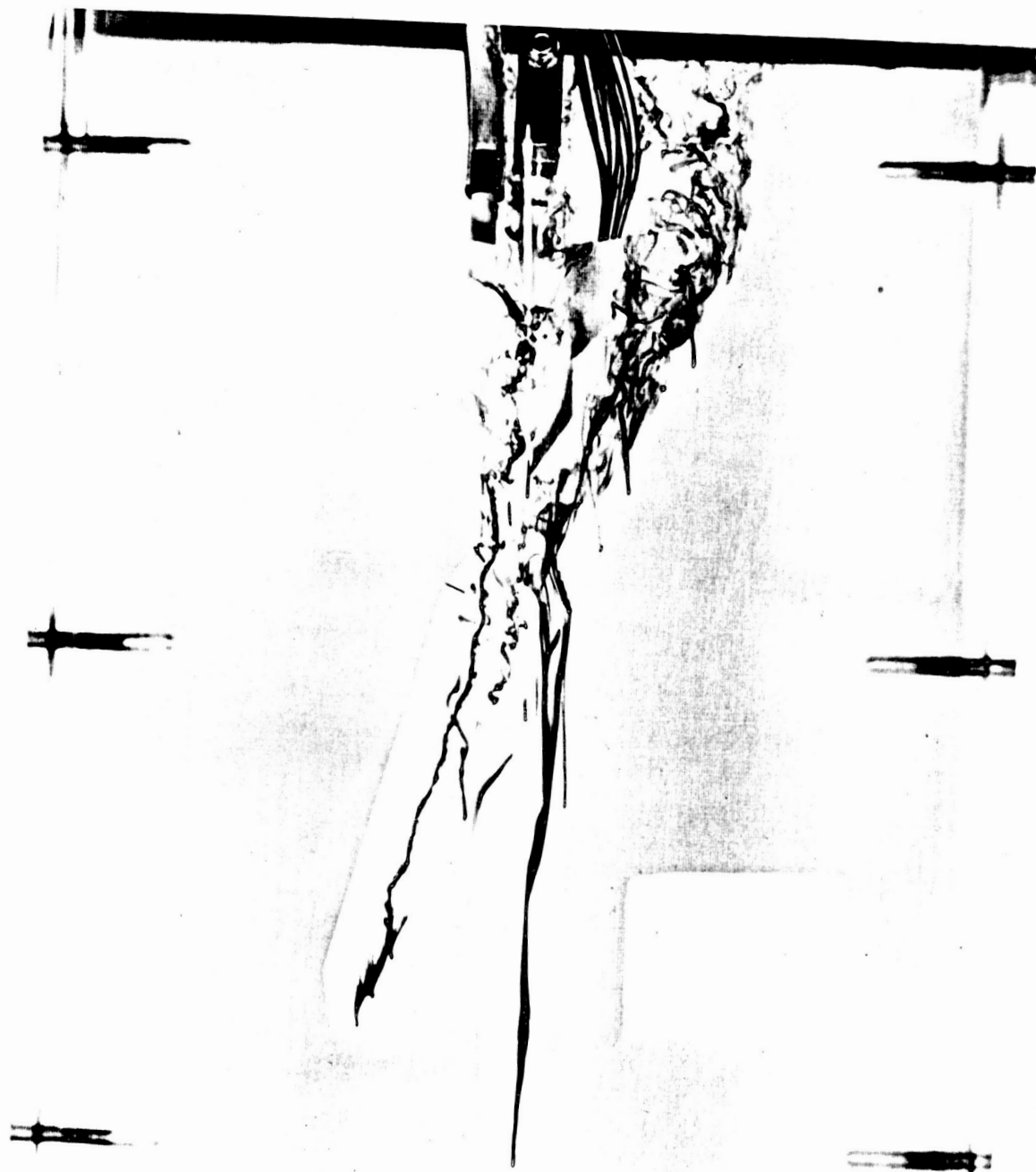


Figure. 4. Spanwise vortex patterns observed around an oblique wing configuration in a water tunnel at $Re = 23,000$, sweep $= 65^\circ$, and $\alpha = 10^\circ$.

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